

# Unusual displacement of H I due to tidal interaction in Arp 181

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## ABSTRACT

We present results from GMRT H I 21 cm line observations of the interacting galaxy pair Arp 181 (NGC 3212 and NGC 3215) at  $z = 0.032$ . We find almost all of the detected H I (90%) displaced well beyond the optical disks of the pair with the highest density H I located  $\sim 70$  kpc west of the pair. An H I bridge extending between the optical pair and the bulk of the H I together with their H I deficiencies provide strong evidence that the interaction between the pair has removed most of their H I to the current projected position. H I to the west of the pair has two approximately equal intensity peaks. The H I intensity maximum furthest to the west coincides with a small spiral companion SDSS J102726.32+794911.9 which shows enhanced mid-infrared (Spitzer), UV (GALEX) and H $\alpha$  emission indicating intense star forming activity. The H I intensity maximum close to the Arp 181 pair, coincides with a diffuse optical cloud detected in UV (GALEX) at the end of the stellar and H I tidal tails originating at NGC 3212 and, previously proposed to be a tidal dwarf galaxy in formation. Future sensitive H I surveys by telescopes like ASKAP should prove to be powerful tools for identifying tidal dwarfs at moderate to large redshifts to explore in detail the evolution of dwarf galaxies in the Universe.

**Key words:** galaxies: spiral - galaxies: interactions - galaxies: kinematics and dynamics - galaxies: individual: Arp 181 - radio lines: galaxies - radio continuum: galaxies

## 1 INTRODUCTION

Galaxy mergers and interactions play a key role in cosmological evolution, affecting galaxy morphology, the star-formation history by triggering intense bursts of star formation (Barnes & Hernquist 1992), and active galactic nuclei (AGN) via the growth of central supermassive black holes (Springel, Di Matteo & Hernquist 2005). Besides spectacular episodes of star formation, mergers can also lead to a significant amount of the progenitor material being temporarily ejected to large distances in the form of tidal tails and debris. Interacting galaxies, in relatively isolated pairs or galaxy groups, containing at least one gas rich member, are ideally suited to study the ways in which tidally stripped gas evolves, e.g. formation of bridges and tails. Where such interactions take place in a group, the stripped gas evolves under the influence of the intra-group medium (IGM) while at the same time contributing to it. Studying the stripped gas can reveal information about gas dynamics, star formation, IGM enrichment and the formation of tidal dwarf galaxies (TDGs).

Star formation beyond the galaxy disks and the principles gov-

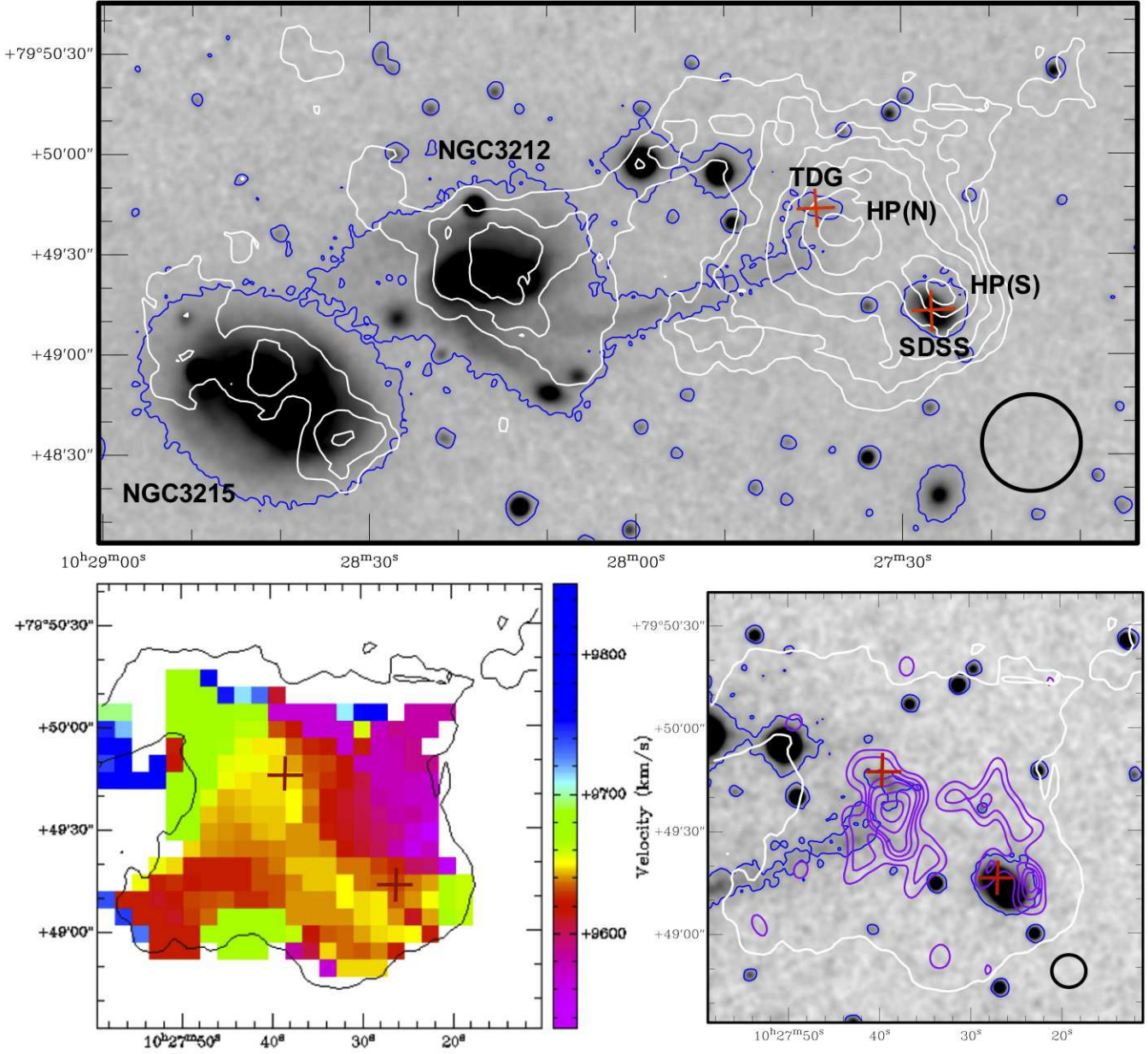
erning it have attracted a lot of recent attention (Sun et al. 2010) and the advent of ultraviolet (UV) and mid-infrared (MIR) telescopes like GALEX and Spitzer have enabled major advances in such studies. There were reports that some tidal bridges, tails and debris containing large amounts of H I also have blue optical counterparts, although it is not always clear whether the blue colour arises from young stars removed from the interacting galaxies or in-situ star formation from tidally stripped gas. Recent high-resolution MIR and UV observations of some of these blue counterparts show that they are recently formed stellar clumps (Smith et al. 2007; Hibbard et al. 2005; Neff et al. 2005). Atomic and molecular gas observations of such systems provide information for determining the conditions under which star formation is triggered in these regions.

If gas densities and environmental conditions within the tidally ejected material are favourable, self-gravitating bodies with masses typical of dwarf galaxies may host star forming regions (Duc et al. 2000; Duc & Mirabel 1999). These entities known as tidal dwarf galaxies (TDGs) have almost always been found within tidal debris. Being born of tidally stripped material TDGs have relatively high metallicities compared to normal dwarfs and a lower dark matter content (This is model dependent, see Barnes & Hern-

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quist 1992a, Bournaud et al. 2007) as well as hosting a mix of old and young stellar populations (Duc 2011).



**Figure 1.** The top panel shows the low-resolution H I column density contours (white) overlaid on SDSS g – band image of the Arp 181 system. The column density levels are  $10^{20} \text{ cm}^{-2} \times (1.3, 2.2, 3.3, 4.4, 5.5, 6.6)$ . The diffuse object suggested as a TDG is marked with a red cross as is SDSS J102726.32+794911.9 and are labeled TDG and SDSS respectively. The blue contours mark the faint limit for the g–band image and clearly show tidal tail and the blue diffuse object (TDG) at the end of the tail emanating from NGC 3212. The two H I peaks HP(N) and HP(S) and the principal galaxies are also labelled. The beam is indicated with the black ellipse. The lower left panel shows the low resolution velocity field of the tidal debris in colour. The black contour is the outermost column density contour as in the top panel and to show the area of the sky presented in this image. The lower right panel shows the high-resolution H I column density contours of the tidal debris overlaid on the SDSS–ugr image of region containing the TDG and SDSS J102726.32+794911.9 . The column density levels are  $10^{20} \text{ cm}^{-2} \times (1.9, 3.5, 5.5, 6.8, 8.7, 9.9, 12.9, 14.5)$ . The beam is indicated with black ellipse. The axes are right ascension and declination in J2000 coordinates.

Due to active ongoing star formation they normally have characteristic blue colours and high stellar velocity dispersions. Typical H I masses of TDGs are a few times  $10^8 M_\odot$  and stellar masses are a few times  $10^9 M_\odot$  (Duc et al. 2000). Besides contributing to the dwarf galaxy population, TDGs provide us with further insights towards understanding galaxy evolution (Duc 2011; Kaviraj et al. 2012).

In addition to tidally stripped gas and galactic winds (Ryan-Weber et al. 2004), in situ star formation in tidal debris can be an important source of IGM enrichment. Ryan-Weber et al. (2004) estimate that a star-formation rate (SFR) as low as  $1.5 \times 10^{-3} M_\odot \text{ yr}^{-1}$  maintained for 1 Gyr, can raise the IGM metallicity by  $\sim 1 \times 10^{-3}$  solar. This value compares well with the “metallicity floor”  $\sim 1.4 \times 10^{-3}$  solar in the damped Lyman alpha (DLA) gas, observed over a redshift range of 0.5 to 5 (Prochaska 2003).

H I 21-cm neutral hydrogen observations are a powerful tool for probing the evolution of tidal debris and identifying TDG candidates. In this Letter we present one of the most spectacular cases of the impact on H I of a tidal interaction between a pair of spirals, NGC 3212 and NGC 3215, which make up the Arp 181 system and possibly a third small galaxy. NGC 3212 has been classified as an ‘S?’ galaxy at a redshift of 0.0324, while NGC 3215 has been classified as an ‘SB?’ galaxy at a redshift of 0.0316 (de Vaucouleurs et al. 1992). We adopt a distance of 130 Mpc (assuming  $H_0=75$ ) for the system and at this distance 1 arcmin translates to  $\sim 39.4$  kpc.

## 2 OBSERVATIONS

H I in Arp 181 was observed with the Giant Metrewave Radio Telescope (GMRT) on December 31st, 2008. Further details of the observations are given in Table 1. The baseband bandwidth used was 8 MHz for the H I 21-cm line observations giving a velocity resolution of  $\sim 13 \text{ km s}^{-1}$ . To improve the signal to noise ratio the velocity resolution was smoothed to  $\sim 26 \text{ km s}^{-1}$  to produce the H I maps presented in this Letter.

The GMRT data were reduced using Astronomical Image Processing System (AIPS) software package. Bad data from malfunctioning antennas, antennas with abnormally low gain and/or radio frequency interference (RFI) were flagged. The flux densities are on the scale of Baars et al. (1977), with flux density uncertainties of  $\sim 5\%$ . The H I cubes were produced following continuum subtraction in the uv domain using the AIPS tasks ‘UVSUB’ and ‘UVLIN’. The task ‘IMAGR’ was used to obtain the final cleaned H I image cubes. From these cubes the integrated H I and H I velocity field maps were extracted using the AIPS task ‘MOMNT’ (USING A  $3\sigma$  CUT-OFF). To analyse the H I structures, we produced image cubes of different resolutions by tapering the data with different uv limits AND USING UNIFORM WEIGHTS FOR THE HIGH RESOLUTION MAPS.

## 3 OBSERVATIONAL RESULTS

Figure 1 (upper panel) shows the integrated H I low-resolution emission (white contours) in Arp 181, overlayed on a smoothed ( $\sim 2''$ ) Sloan Digital Sky Survey (SDSS) g-band image. NGC 3212, NGC 3215, the tidal bridge, the two H I intensity peaks in the western H I mass (the main concentration of H I west of the principal pair) and the two optical entities associated with the western H I mass are labelled in the image. The blue contour marks the approximate faint

**Table 1.** GMRT observation details

Frequency	1376.4 MHz
Observation Date	31st December, 2008
primary calibrator	3C286
Phase Calibrators	0410+769 (5.76 Jy)
(flux density)	1313+675(2.40 Jy)
Integration time	8.0 hrs
BASEBAND BANDWIDTH	8 MHz
NUMBER OF CHANNELS	128
primary beam	24' at L BAND
Low resolution beam	32.3'' $\times$ 30.9'' (PA = 40.3 °)
High resolution beam	10.5'' $\times$ 10.5''
rms for low-resolution map	0.70 mJy beam <sup>-1</sup>
rms for high-resolution map	0.47 mJy beam <sup>-1</sup>
RA (pointing centre)	10 <sup>h</sup> 28 <sup>m</sup> 28. <sup>s</sup> 5
DEC (pointing centre)	+79° 49' 05.0''

limit for the SDSS g-band emission. The lower left panel of Figure 1 shows the velocity field of the western H I mass. The colour scheme in velocity field has been used to highlight the velocity gradient within the H I mass. The lower right panel of Figure 1 shows the high-resolution H I image (contours) of a zoom in to the region where most of the H I mass in the system was detected.

Figure 1 (upper panel), shows that almost the entire H I mass of the system is detected well beyond the optical disks of NGC 3212 and NGC 3215 and is connected to NGC 3212 by a low density H I bridge. The H I bridge is not coincident with the optical tidal tail but runs parallel and to the north of it. The western H I mass has two distinct intensity maxima at positions 10<sup>h</sup> 27<sup>m</sup> 37.<sup>s</sup>1, 79° 49' 36.7'' and 10<sup>h</sup>27<sup>m</sup> 25.<sup>s</sup>1, 79° 49' 16.62'', hereafter referred to as HP(N) and HP(S) respectively. HP(S) approximately coincides with a small blue spiral SDSS J102726.32+794911.9 which has no published redshift. however information in [http://www.etsu.edu/physics/bsmith/research/sg/sara\\_s.g.html](http://www.etsu.edu/physics/bsmith/research/sg/sara_s.g.html) confirms this galaxy is at similar redshift to the ARP 181 system. HP(N) is close to a diffuse blue object at the projected end of the optical tidal tail emanating from NGC 3212 (Figure 1).

The total H I flux density recovered from this system from the GMRT observations is  $3.3 \pm 0.2 \text{ Jy km s}^{-1}$  compared to the single dish value of  $2.3 \pm 1.5 \text{ Jy km s}^{-1}$  (Theureau et al. 1998). Using a GMRT integrated H I map, the H I content of individual galaxies and the western mass was estimated. The two galaxies, NGC 3212 and NGC 3215 contain H I of  $2.7 \times 10^9 M_\odot$  and  $7.9 \times 10^8 M_\odot$  respectively while the western H I mass along with the tidal bridge is  $9.5 \times 10^9 M_\odot$ . The uncertainty on these estimates are  $\sim 10\%$ . The velocity field of the western H I mass shows no signs of regular rotation at this velocity resolution. However there is a gradient from both east and west, converging near the positions of the H I intensity maxima, especially HP(N).

## 4 DISCUSSION

Within the limits of current spectroscopic data Arp 181 appears to be a fairly isolated system. The nearest similar size neighbour is CGCG 350-053 projected at an angular distance of  $\sim 30.4'$  (1.4 Mpc) with a velocity separation of  $\sim 2000 \text{ km s}^{-1}$ . There are several small galaxies projected close to Arp 181, but they lack spectroscopic data to confirm their distances. Thus it is possible Arp 181 is a galaxy group dominated by NGC 3212 and NGC 3215. The system has been previously observed with



Spitzer (Smith et al. 2007), GALEX (Smith et al. 2010a) and in H $\alpha$  ([http : //www.etsu.edu/physics/bsmith/research/sg/sara\\_g.html](http://www.etsu.edu/physics/bsmith/research/sg/sara_g.html)).

Based on their GALEX and optical observations, Smith et al. (2010b) conclude this system potentially hosts one or more TDGs. They suggested the two objects at positions  $10^{\text{h}} 27^{\text{m}} 26.^{\text{s}}2, 79^{\circ} 49' 12.3''$  (SDSS J102726.32+794911.9) and  $10^{\text{h}} 27^{\text{m}} 40.^{\text{s}}1, 79^{\circ} 49' 45.3''$  are TDG candidates. Their optical spectroscopic observations confirmed the galaxy at position  $10^{\text{h}} 27^{\text{m}} 26.^{\text{s}}2, 79^{\circ} 49' 12.3''$  (SDSS J102726.32+794911.9) is associated with the system. This galaxy appears to have spiral features in the SDSS images, and is extremely blue in NUV – g. According to Smith et al. (2010b), this may be a dwarf galaxy which is a part of the group or a recently detached TDG. The object at position  $10^{\text{h}} 27^{\text{m}} 40.^{\text{s}}1, 79^{\circ} 49' 45.3''$ , is their second TDG candidate, although its association with the Arp 181 system remains to be confirmed spectroscopically (Smith et al. 2010b). The GALEX observations at the position of this second candidate showed it to be a diffuse clump of UV emission at the tip of the optical tidal tail emanating from NGC 3212. Unlike SDSS J102726.32+794911.9, which is bright in Spitzer and SDSS images, this clump is prominent only in UV. In Figure 1 (upper panel) this second TDG candidate is faintly visible at the tip of the tidal tail emanating from NGC 3212 and is near to HP(N).

Our observations reveal only moderate H I emission from the interacting pair, NGC 3212 and NGC 3215, with the bulk of the H I emission detected in the western H I mass well beyond the optical disks of the Arp 181 pair. The two dwarf systems mentioned in Smith et al. (2010b) are both projected on the western H I mass. Such a large amount of H I ( $\sim 9.5 \times 10^9 M_{\odot}$ ) beyond the principal galaxies' optical disks and associated with only small optical counterparts or star forming regions is highly unusual. Two likely scenarios to account for this unusual H I distribution are discussed below.

Tidal interaction between NGC 3212, NGC 3215 and SDSS J102726.32+794911.9 seems to be a likely source of the western H I mass as there is no nearby neighbour of similar size in similar redshift range within  $\sim 3$  Mpc radius. Also both the Arp 181 pair galaxies are severely H I deficient indicating H I has been removed from the galaxies. A method to determine gas loss from a spiral is to compare its H I surface density to that of a sample of field spirals of the same morphological type. The parameter used to estimate the H I deficiency is  $\log \frac{M_{\text{HI}}}{D_i^2}$  (Haynes & Giovanelli 1984), where  $M_{\text{HI}}$  is the total H I mass of a galaxy and  $D_i$  is the optical major isophotal diameter (in kpc) measured at or reduced to a surface brightness level  $m_B = 25.0$  mag/arcsec<sup>2</sup>. While Haynes & Giovanelli (1984) used the UGC major diameters, we have used the RC3 diameters and used the modified values from Sengupta & Balasubramanyam (2006). The expected value of this parameter for an early type spiral (Sb) is  $6.91 \pm 0.26$ . Since morphological sub-classifications are not available for NGC 3212 and NGC 3215, we compared these galaxies against Sb type spirals. The H I surface density values for NGC 3212 and NGC 3215 are 5.90 and 5.66, respectively, indicating they are H I deficient by a factor of 10. Because of the morphological type, diameter and H I mass uncertainties, the values for the H I deficiencies are themselves highly uncertain. Despite this it remains clear that taken together the pair is highly H I deficient. This lost H I is likely to be a major source of the H I in the western H I mass. The tidal bridge connecting NGC 3212 to the western H I mass also supports that this H I mass is a tidal debris from the Arp 181 interaction. The small dwarf system, SDSS J102726.32+794911.9, may also be participating in the interaction. The high-resolution H I image (lower right

of Figure 1) shows the HP(S) to be offset by  $\sim 5''$  (a beam) from the optical centre of SDSS J102726.32+794911.9 and its H I extends in the direction of the candidate TDG. However, given its size, the H I mass contributed by this system is likely to be a small fraction of the western H I mass.

Another scenario for the origin of the western H I mass could be that of SDSS J102726.32+794911.9 being a low surface brightness (LSB) galaxy and the western H I mass is at least partially the galaxy's H I disk. Under this scenario HP(S) is the central region of the LSB. The SDSS images show distinct spiral pattern in SDSS J102726.32+794911.9 and thus it is possible that only the central bright part of this galaxy is visible. However, two significant observational facts do not support this scenario. The H I column density peak value for the high-resolution map reaches a higher value than the low-resolution map, indicating the H I to be compact and clumpy. The peak values and dimensions of the H I clumps in the high-resolution H I map are similar for HP(N) and HP(S), consistent with both being similar entities. Also contrary to what is expected of a big LSB spiral, we find no signs of regular rotation in this H I mass. Instead the velocity field of the western H I mass is chaotic and (lower panel Figure 1) shows an interesting gradient suggesting infall of gas from the eastern and the western sides towards the central region. Thus we find this H I mass to be behaving more like tidal debris than an interacting massive LSB disk.

As explained in Section 3, the debris has two peaks, HP(N) and HP(S), and we confirm these peaks coincide, with small offsets ( $\sim 5''$ ), with the two dwarf galaxies described in Smith et al. (2010b), the TDG and SDSS J102726.32+794911.9 respectively. From the channel images and the GMRT spectrum, we find the H I velocity of HP(N) is  $9659 \text{ km s}^{-1}$ . The high-resolution H I zoomed in image of HP(N) and HP(S) (Figure 1) shows a diffuse blue object close to HP(N), at the tip of the tidal tail emanating from NGC 3212. This is the TDG candidate suggested by Smith et al. (2010b). The H I column density maximum in the low-resolution ( $\sim 30''$ ) map for this object is  $6.6 \times 10^{20} \text{ cm}^{-2}$ . At a distance of 130 Mpc, a  $30''$  beam samples  $\sim 18$  kpc. The H I mass of the debris and the H I column density values are a good match with those found in TDGs (Braine et al. 2001; Duc et al. 1997). The high-resolution ( $\sim 10''$ ) H I map further confirms the H I peak to be associated WITH the TDG as well as H I extension to the east towards the optical tidal tail of NGC 3212.

HP(S) on the other hand, coincides with the small, very blue galaxy SDSS J102726.32+794911.9, which Smith et al. (2010b) suggested is either a dwarf galaxy or a recently detached TDG. Our high-resolution H I image (lower right of Figure 1) shows an offset ( $\sim 5''$ ) between the galaxy and the H I peak. From the GMRT spectrum, we find the H I velocity of HP(S) to be  $\sim 9575 \text{ km s}^{-1}$ , indicating it is either interacting with the tidal debris from the Arp pair or formed from it. The latter option is unlikely as the galaxy is bright in SDSS z – band suggesting presence of an old stellar population and its faint spiral structure would be unusual for a recently formed TDG. Unlike the diffuse optical structure associated with HP(N), SDSS J102726.32+794911.9 is bright in the Spitzer images implying strong star formation activity, possibly triggered by interaction. Additionally, the offset between HP(S) and SDSS J102726.32+794911.9 may be the result of an ongoing interaction with the H I debris from the Arp 181 pair and the H I disk of SDSS J102726.32+794911.9, which is itself part of the Arp 181 system.

Massive displacement of H I from the galaxy disk due to tidal interaction has been witnessed in a few other cases also (Hota, Saikia & Irwin 2007; Rupen, Hibbard & Bunker 2001; Duc et al. 1997). Of these, the H I distribution of the Arp 181 sys-

tem very closely resembles that in Arp 105 (Duc et al. 1997). In the Arp 105 system, bulk of the  $\sim 6 \times 10^9 M_\odot$  H I was detected at the end of a 100 kpc long optical tidal tail originating from the H I rich spiral NGC 3561A, with the disk of NGC 3561A containing only  $\sim 5 \times 10^7 M_\odot$  of H I. The bulk of the H I is connected to NGC 3561A by a faint and discontinuous H I bridge and is also host to a TDG candidate A105N. The Arp 105 system is known as an example of extreme gas segregation, with the H I and CO in this system having been completely segregated as a result of interaction between NGC 3561A and NGC 3561B. Molecular gas mass  $\sim 10^{10} M_\odot$  was detected in the NGC 3561A disk with no detection of molecular gas in the tidal debris or anywhere else in the system (Duc et al. 1997). Based on Arp 105, it is possible that the disks of NGC 3215 and NGC 3212 are H I deficient but have retained their molecular gas. So molecular gas observations are required for Arp 181 to get a complete picture of the gas distribution of this interesting system.

## 5 SUMMARY AND CONCLUDING REMARKS

In summary, Arp 181 appears to be at a particularly interesting stage of its evolution following the interaction between at least two, possibly three, of its members during which most of the H I in the system has been stripped from the parent galaxies and  $9.5 \times 10^9 M_\odot$  of H I tidal debris is now observed  $\sim 70$  kpc west of the principal galaxy pair. We find this H I debris to be in a state of rapid evolution including hosting at least one tidal dwarf in formation. We confirm the radial velocity of this H I in the region of this TDG is  $\sim 9659 \text{ km s}^{-1}$ . H I debris also contains another small star forming galaxy, its optical and IR properties suggest it to be a pre-existing member of Arp 181. Arp 181 is a system at moderate redshift  $\sim 0.032$ . Future sensitive H I surveys by telescopes such as Australian Square Kilometre Array Pathfinder (ASKAP) (Deboer et al. 2009; Johnston et al. 2008) should prove to be very powerful tools for identifying tidal dwarfs at moderate and large redshifts to explore in detail the evolution of dwarf galaxies in the Universe.

## 6 ACKNOWLEDGMENTS

We thank the staff of the *GMRT* who have made these observations possible. The *GMRT* is operated by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. We thank the reviewer for his/her useful comments and suggestions. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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